NE-1150

- 1 -

1   TITLE OF THE INVENTION
2   Constant Current Circuit and Active Filter Circuit Using the Same
3   BACKGROUND OF THE INVENTION
4   Field of the Invention
5   The present invention relates generally to active filter circuits and
6   more specifically to an active filter circuit driven by a constant current circuit.
7   Description of the Related Art
8   A typical active filter circuit includes a Gm-C filter which is driven by
9   a reference current supplied from a constant current source. Usually, the
10   active filter circuit is formed on a common semiconductor substrate. Due to
11   temperature drift or variability of manufacturing process, all resistors of the
12   substrate are uniformly affected so that their resistance values deviate from
13   their rated values. This results in the reference current varying in a direction
14   opposite to the direction of deviation of all resistors. The effect of the varying
15   reference current is combined with a resistance deviation that occurs in the
16   active filter and causes a deviation of its cut-off frequency from the desired
17   frequency.
18   Japanese Patent Publication 1998-284989 discloses an active filter
19   circuit which includes a temperature-compensation current source as an extra
20   power supply unit of main DC power source. Currents produced by the DC
21   power source and the extra power supply unit are combined to drive a Gm-C
22   filter. By varying the input current of the Gm-C filter according to
23   temperature drift, the cut-off frequency of the filter is kept constant.
24   However, the use of the extra power unit for temperature compensation
25   requires the circuit designer to estimate all possible temperature variations
26   and prepare reference test data based on the estimated temperature
27   variations. The reference test data is used to adjust the output current of the
28   extra power unit corresponding to the estimated temperature variations.
29   While this prior art is satisfactory if the estimated temperature variations are
30   accurate, the disclosed technique is limited for a particular type of filters.

NE-1150

-2-

1   Furthermore, the prior art is incapable of compensating for the uniformly

2   drifted variations of resistors caused by variability of manufacturing process.

3   Japanese Patent Publication 1995-321602 discloses a time-constant

4   control circuit which forms part of an active filter. The time-constant control

5   circuit is formed by a pair of transistors and a resistor coupled between the

6   emitters of the transistors. Two current sources are respectively connected to

7   the transistors. One of the transistors has its base biased at a reference

8   voltage. A variability detector is provided for detecting an RC error caused

9   by variability in the manufacturing process of integrated circuits. Based on

10 the detected RC error, a control voltage is supplied from the variability

11 detector to the base of the other transistor and the current sources. The time-

12 constant control circuit produces a control voltage that renders the

13 transconductance of the active filter unaffected by the RC error.

14   However, the prior art requires that the variability detector be

15 implemented with a Gilbert multiplication circuitry which adds to the size

16 and complexity of the integrated circuit.

17   SUMMARY OF THE INVENTION

18   It is therefore an object of the present invention to provide a simple yet

19 effective solution for compensating for uniformly drifting variations of

20 resistors of an active filter circuit formed on a common semiconductor chip,

21 regardless of varying temperature and variability of manufacturing process.

22   A further object of the present invention is to provide a constant

23 current circuit which can be universally used with an active filter for

24 compensating for uniformly drifting variations of resistors of the active filter

25 and the constant current source formed on a common semiconductor chip.

26   According to one aspect of the present invention, there is provided a

27 constant current circuit including a plurality of resistors formed on a

28 semiconductor substrate, comprising a first current source for producing a

29 first current of constant magnitude regardless of resistance variations which

30 can occur uniformly in the resisters, and a second current source for

NE-1150

-3-

1   producing a second current of magnitude which is inversely variable with the

2   resistance variations. The first and second current sources are connected to

3   each other for producing an output current which is equal to a difference

4   between the first and second currents.

5   According to a second aspect, the present invention provides a

6   constant current circuit including a plurality of resistors formed on a

7   semiconductor substrate. The constant current circuit comprises a first group

8   of parallel transistors having emitters connected via respective resistors to a

9   voltage source and having collectors connected together to an output

10   terminal, a second group of parallel transistors having emitters connected via

11   respective resistors to the voltage source and having collectors connected to

12   each other, a constant current source connected between the collectors of the

13   second group of transistors and ground to produce a constant current. The

14   first and second groups of transistors have their bases connected together to

15   form a current mirror, whereby a current equal to the constant current is

16   drawn by the first group of transistors to the output terminal. Transistor-

17   resistor circuitry is provided for drawing a current inversely variable with

18   uniform resistance variations of the semiconductor substrate from the output

19   terminal to ground.

20   According to a third aspect, the present invention provides an active

21   filter circuit having a plurality of resistors formed on a semiconductor

22   substrate, comprising a first current source for producing a first current of

23   constant magnitude regardless of resistance variations which can occur

24   uniformly in the resistors, a second current source for producing a second

25   current of magnitude which is inversely variable with the resistance

26   variations, the first and second current sources being connected to each other

27   for producing an output current which is equal to a difference between the

28   first and second currents, and an active filter driven by the output current for

29   filtering an input signal.

30   According to a fourth aspect, the present invention provides an active

NE-1150

-4-

1　filter circuit having a plurality of resistors formed on a semiconductor

2　substrate. The active filter circuit comprises a first group of parallel

3　transistors having emitters connected via respective resistors to a voltage

4　source and having collectors connected together to an output terminal, a

5　second group of parallel transistors having emitters connected via respective

6　resistors to the voltage source and having collectors connected to each other,

7　and a constant current source connected between the collectors of the second

8　group of transistors and ground to produce a constant current, the first and

9　second groups of transistors having their bases connected together to form a

10　current mirror, whereby a current equal to the constant current is drawn by

11　the first group of transistors to the output terminal. Transistor-resistor

12　circuitry is provided for drawing a current inversely variable with uniform

13　resistance variations of the semiconductor substrate from the output terminal

14　to ground. Further provided are a pair of switching circuits which are driven

15　by the output current for alternately assuming a conducting state according

16　to polarity of an input signal, and resistor-capacitor circuitry connected

17　across the switching circuits to produce a filtered output signal.

18　　　　　　　　BRIEF DESCRIPTION OF THE DRAWINGS

19　　　　The present invention will be described in detail further with reference

20　to the following drawings, in which:

21　　　　Fig. 1 is a circuit diagram of an active filter circuit incorporating a

22　constant current source of the present invention;

23　　　　Fig. 2 is a circuit diagram of the constant current source constructed

24　according to a first embodiment of the present invention;

25　　　　Fig. 3 is a circuit diagram of the constant current source constructed

26　according to a second embodiment of the present invention; and

27　　　　Fig. 4 is a circuit diagram of the constant current source constructed

28　according to a third embodiment of the present invention.

29　　　　　　　　　　DETAILED DESCRIPTION

30　　　　In Fig. 1, the active filter circuit of the present invention is comprised

-5-

1   of a Gm-C filter 10 and a constant current source 11, both of which are

2   integrated on a common semiconductor substrate 12. Filter 10 includes a pair

3   of NPN transistors 20 and 21 whose bases are respectively coupled to input

4   terminals 31 and 32 where an input alternating voltage is applied. The

5   collectors of transistors 20, 21, which are connected to the voltage source Vcc

6   via current sources 22 and 23, are ac-coupled by a capacitor 30. The collectors

7   of these transistors 20, 21 are further connected to output terminals 34, 35

8   from which an output alternating voltage is delivered. The emitters of the

9   transistors 20, 21 are dc-coupled by a resistor 33 and further connected to the

10   collectors of NPN transistors 24, 25, respectively. The bases of transistors 24,

11   25 are connected to a circuit node 36 and the emitters of transistors 24, 25 are

12   connected to ground via respective resistors 26, 27.

13   Constant current source 11 of the present invention, which is

14   connected between the voltage source Vcc and ground, includes current

15   sources 40 and 41 and a drive circuit 42 which drives the current sources 40

16   and 41. A circuit node between the current sources 40 and 41 is connected to

17   an output terminal 43 from which an output current I_{out} is supplied to the

18   circuit node 36 of the active filter 10.

19   Details of the constant current source 11 of a first embodiment of the

20   present invention are shown in Fig. 2. In this embodiment, the drive circuit

21   42 drives the current source 40 with a current I x N and drives the current

22   source 41 with a current I x N/M, where M is the number of collector-

23   coupled PNP transistors provided in each of the current source 40 and the

24   drive circuit 42 that form a current mirror and N is the number of transistors

25   provided in the current source 41 that forms part of the current mirror. In the

26   present invention, N and M are assumed to be 1 and 2, respectively.

27   Current source 40 comprises a pair of PNP transistors 50, 51 whose

28   emitters are respectively connected via resistors 52, 53 to the voltage source

29   Vcc and whose collectors connected together to the output terminal 43. Drive

30   circuit 42 comprises a pair of PNP transistors 70, 71 whose emitters are

NE-1150

-6-

1　　respectively connected via resistors 72, 73 to the voltage source Vcc and

2　　whose collectors are connected together to a current source 74 and to the base

3　　of a PNP transistor 75 whose emitter is connected to the bases of transistors

4　　70, 71 and whose collector is connected to ground through a resistor 76.

5　　　　　Current source 74 is formed of resistors. These resistors are provided

6　　external to the semiconductor substrate 12 so that current source 74 can

7　　deliver a constant current "I", regardless of temperature drift or variability of

8　　manufacturing processes which would uniformly affect the resistivity of all

9　　the internally provided resistors of the substrate 12.

10　　　　　The bases of PNP transistors 50, 51 of current source 40 and the bases

11　　of transistors 70, 71 of driver 42 are connected together to form a current

12　　mirror and the PNP transistor 60 forms part of the current mirror by coupling

13　　its base to the bases of transistors 50, 51, 70, 71. As a result of the current

14　　mirror relation, the same current I is caused to flow through the collector-

15　　coupled PNP transistors 50, 51 of current source 40 to the output terminal 43

16　　as the current I drawn through the collector-coupled PNP transistors 70, 71

17　　by the constant current source 74 to ground.

18　　　　　Current source 41 is of a V_{BE}-dependent type. Current source 41

19　　includes a PNP transistor 60 whose base is connected to the bases of

20　　transistors 50, 51, 70, 71. The emitter of transistor 60 is connected to the

21　　voltage source Vcc via a resistor 61 and its collector is connected to a circuit

22　　node N1 to which the base of an NPN transistor 62 and the collector of an

23　　NPN transistor 63 are connected. The emitter of transistor 62 and the base of

24　　transistor 63 are connected together to a circuit node N2 which is grounded

25　　via a resistor 65. The connector of transistor 62 is connected to the output

26　　terminal 43. The emitter of transistor 63 is connected to ground via a resistor

27　　64.

28　　　　　In the current source 41, the PNP transistor 60 draws a current from

29　　the voltage source Vcc to ground via transistor 63 and resistor 64. Since the

30　　number of PNP transistors provided in the current source 41 is 1/2 of the

NE-1150

-7-

1 PNP transistors of each half of the current mirror circuit, the current that

2 flows through the node N1 is one-half of the current I.

3   NPN transistors 62 and 63 cause a current I_1 to flow from the output

4 terminal 43 to ground through resistor 65. This current is given by Equation

5 (1).

6
$$I_1 = \frac{V_{N2}}{R_5} \tag{1}$$

7 where, V_{N2} is the potential at the circuit node N2 and R_5 is the value of

8 resistor 65. Since the potential V_{N2} is expressed as follows:

9
$$V_N = V_{BE} + \frac{N}{M} I \times R_4 \tag{2}$$

10 Since N = 1 and M = 2, Equation (2) is rewritten as:

11
$$V_{N2} = V_{BE} + \frac{1}{2} I \times R_4 \tag{3}$$

12 where, V_{BE} is the base-emitter voltage of transistor 63 and R_4 is the value of

13 resistor 64. Current I_1 is thus given by Equation (4).

14
$$I_1 = \frac{V_{BE} + \frac{1}{2} I \times R_4}{R_5} \tag{4}$$

15 Since the output current I_{out} is equal to the difference between I and I_1, the

16 following relation holds:

17
$$I_{out} = I - I_1 = I - \frac{V_{BE} + \frac{1}{2} I \times R_4}{R_5} \tag{5}$$

18   When the current I_{out} is supplied to the node 36 of active filter 10, the

19 NPN transistors 24 and 25 are turned ON. If an input alternating voltage is

20 applied to the terminals 34 and 35, the NPN transistors 20 and 21 are turned

21 ON and OFF in a complementary fashion depending on the polarity of the

22 input voltage. As a result, when the transistor 20 is ON, it draws a current

23 from the current source 22 to ground through transistor 24 and resistor 26,

24 and when the transistor 21 is ON, it draws a current from the current source

NE-1150

-8-

1   23 to ground through transistor 25 and resistor 27.

2   If the input voltage is a low frequency signal, the capacitor 30

3   functions as a high impedance element and its presence can be ignored.

4   Hence, the output terminals 34 and 35 are in an open circuit condition,

5   causing an alternating voltage to appear thereacross. If the input voltage is a

6   high frequency signal, the capacitor 30 functions as a low impedance element.

7   Hence, the output terminals 34 and 35 are in a short-circuit condition, causing

8   no output voltage to appear thereacross. In this way, the active filter 10

9   operates as a low-pass filter. The cut-off frequency f_c of the low-pass filter is

10 given by Equation (6).

11
$$f_c = \frac{1}{2\pi\sqrt{C \times \frac{1}{g_m}}} \tag{6}$$

12
$$g_m = \frac{1}{R + \frac{2 \times V_{cc}}{I_{out}}} \tag{7}$$

13 where C is the capacitance of capacitor 30, R is the value of resistor 33, and

14 V_{cc} is the power voltage of the voltage source Vcc.

15   Current I_1 of Equation (4) varies inversely with resistance variations

16 which can occur uniformly in all internal resistors of the semiconductor

17 substrate 12 as follows.

18   If the temperature of semiconductor substrate 12 rises, all resistors on

19 the substrate 12 increase uniformly, and the current I_1 of current source 41

20 decreases, while current I of current source 74 remains unaffected due to the

21 provision of resistors external to the substrate 12. Because of the current

22 mirror relation to the drive circuit 42, the current I drained through the

23 current source 40 to the output terminal 43 is also unaffected. Therefore, the

24 output current I_{out} increases as seen from Equation (5). This increase would

25 cause the transconductance g_m to decrease. However, Equation (7) shows

26 that a concomitant increase in the resistance R (of resistor 33) produc s an

NE-1150

-9-

1   opposing effect on this decrease. On the other hand, if the temperature of

2   substrate 12 lowers, all of its resistors decrease uniformly and the current I_1

3   increases while the output current I_{out} decreases, tending to increase the

4   transconductance. A concomitant decrease in the resistance R counteracts

5   this increase in transconductance. If the resistance R is appropriately

6   determined in relation to the output current I_{out}, such temperature-

7   dependent mutual-conductance variations can be completely nullified, so

8   that the cut-off frequency f_c can be maintained constant under a varying

9   temperature.

10   Active filter 10 and the constant current source 11 cooperate in much

11   the same way when all the internal resistors of the substrate 12 are caused to

12   offset uniformly from their nominal values due to variability of

13   manufacturing processes.

14   The present invention thus eliminates the need to prepare reference

15   measurement data for circuit testing. Therefore, the constant current source

16   11 of the present invention can be universally used with various active filters.

17   A constant current source 11A, shown in Fig. 3, is a second

18   embodiment of the present invention. This embodiment differs from the

19   previous embodiment in that it replaces the V_{BE}-dependent type current

20   source 41 with a V_{CC}-dependent type current source 41A.

21   Current source 41A includes an NPN transistor 81 whose collector is

22   connected to the output terminal 43. The base of transistor 81 is connected to

23   a circuit node N3 of resistors 82 and 83 connected in series between Vcc and

24   ground. Transistor 81 has its emitter coupled to ground through a resistor 84.

25   The potential at node N3 is given by Equation (8) and the transistor 81 draws

26   a current I_2 from the output terminal 43 to ground. Current I_2 is given by

27   Equation (9).

28    $$V_{N3} = \frac{R_{13}}{R_{12} + R_{13}} \times V_{cc} \qquad\qquad (8)$$

NE-1150

- 10 -

1
$$I_2 = \frac{V_{N3} - V_{BE}}{R_{14}} = \frac{R_{13} \times V_{cc}}{(R_{12} + R_{13})R_{14}} - \frac{V_{BE}}{R_{14}} \qquad (9)$$

2 where, R_{12}, R_{13} and R_{14} represent the resistances of resistors 82, 83 and 84,

3 respectively, and V_{BE} is the base-emitter voltage of transistor 81. Therefore,

4 the output current I_{out} is obtained as follows:

5
$$I_{out} = I - I_2 = I - \left\{ \frac{R_{13} \times V_{cc}}{(R_{12} + R_{13})R_{14}} - \frac{V_{BE}}{R_{14}} \right\} \qquad (10)$$

6   It is seen from Equations (9) and (10) that when all resistors of the

7 substrate 12 uniformly increase, current I_2 decreases and output current I_{out}

8 increases, and when all resistors uniformly decrease, current I_2 increases and

9 output current I_{out} decreases. The cut-off frequency of the filter 10 is thus

10 maintained constant.

11   A constant current source 11B, shown in Fig. 4, is a third embodiment

12 of the present invention, which differs from the first embodiment in that it

13 replaces the V_{BE}-dependent type current source 41 with a band-gap type

14 current source 41B.

15   Current source 41B includes a pair of PNP transistors 90 and 91 having

16 their base connected to the bases of current-mirror transistors 50, 51, 70, 71,

17 and having their emitters connected to Vcc via resistors 92 and 93. The

18 collector of transistor 90 is connected to the collectors of a group G of "n"

19 parallel transistors of NPN conductivity, while the collector of transistor 91 is

20 coupled to a circuit node N5 to which the collector of an NPN transistor 94

21 are also connected.

22   The emitters of transistor group G are connected together to a point

23 which is connected through resistors 96 an 97 to ground, while the emitter of

24 transistor 94 is connected to a circuit node N4 which is formed between the

25 resistors 96 and 97. Current source 41B further includes an NPN transistor 95

26 whose collector is connected to the output terminal 43, its emitter being

27 coupled through a resistor 99 to ground. The bases of transistors 94, 95 and

—

NE-1150

- 11 -

1 transistor group G are connected together to the circuit node N5. PNP

2 transistors 90 and 91 constitute a current mirror with the PNP transistors 50,

3 51, 70 and 71. Since the PNP transistors 90 and 91 have their collectors not

4 coupled together unlike transistors 50, 51 and 70, 71, one-half of the current I

5 is drawn through each of the transistors 90 and 91 to the circuit node N4,

6 where these currents are summed to produce a current I through the resistor

7 97. Therefore, the potentials V_{N4} and V_{N5} at the circuit nodes N4 and N5 are

8 given by Equations (11) and (12), respectively.

9 $$V_{N4} = I \times R_{17} \tag{11}$$

10 $$V_{N5} = V_{N4} + V_{BE} = V_{N4} + \frac{I \times R_{16}}{2} + V_{GBE} \tag{12}$$

11 where, R_{16} and R_{17} are the respective resistances of resistors 96 and 97, V_{BE} is

12 the base-emitter voltage of transistor 94 and V_{GBE} is the base-emitter voltage

13 of the transistor group G.

14 According to bipolar transistor theory, V_{GBE} of the "n" transistors

15 connected in parallel to transistor 94, is given by Equation (13).

16 $$V_{GBE} = V_{BE} - V_T \times ln(n) \tag{13}$$

17 where, V_T is the volt equivalent of temperature which is expressed as:

18 $$V_T = \frac{k \times T}{q} \tag{14}$$

19 where k is the Boltzmann constant, T is the absolute temperature (Kelvin) and

20 q is the electric charge. From Equations (12) and (13), the voltage developed

21 across the resistor 96 is equal to:

22 $$\frac{1}{2} I \times R_{16} = V_{BE} - V_{GBE} = V_T \times ln(n) \tag{15}$$

23 Hence, the potentials V_{N4} and V_{N5} are given by Equations (16) and (17),

24 respectively.

25 $$V_{N4} = \{2 \times V_T \times ln(n)\} \times \frac{R_{17}}{R_{16}} \tag{16}$$

NE-1150

- 12 -

1
$$V_{N5} = V_{BE} + \{2 \times V_T \times ln(n)\} \times \frac{R_{17}}{R_{16}} \qquad (17)$$

2   The first term of Equation (17), i.e., V_{BE} indicates that the potential V_{N5}

3   varies with a negative temperature characteristic and the second term, i.e., {2

4   $\times V_T \times ln (n)$] indicates that it varies with a positive temperature

5   characteristic, which counteracts the negative temperature characteristic of

6   the first term. The potential V_{N5} at the circuit node N5 is thus kept constant

7   regardless of temperature variations. Since current I_3, which is drawn by

8   transistor 95 to pass through resistor 99 to ground, is given by:

9
$$I_3 = \frac{V_{N5} - V_{BE}}{R_{19}} \qquad (18)$$

10 (where, V_{BE} is the base-emitter voltage of transistor 95 and R_{19} is the value of

11 resistor 99), the output current I_{out} of Fig. 4 becomes:

12
$$I_{out} = I - I_3 = I - \frac{V_{N5} - V_{BE}}{R_{19}} \qquad (19)$$

13   It is seen from Equations (18) and (19) that current I_3 varies inversely

14 with resistance variations and the output current I_{out} varies with the

15 resistance variations.